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CHARACTERISTICS OF THREE PRECISION CIRCUMLUNAR TRAJECTORIES FOR THE YEAR 1968

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SUMMARY

The characteristics of three precision circumlunar trajectories are presented for use in the study of a manned mission in the year 1968. These trajectories have been obtained with the use of a restricted four-body, three-dimensional trajectory program utilizing actual calendar dates and body positions as obtained from U.S. Naval Observatory data. The constraints associated with each of these trajectories are launch from Cape Canaveral, Florida, touchdown in the continental United States, and injection conditions compatible with the capabilities of a booster such as the Saturn vehicle. The injection dates were selected to obtain the trajectory characteristics associated with each of the lunar motions which may be encountered, with a direct launch from Cape Canaveral, that is whether the moon is descending, ascending, or at maximum negative declination at the time of periselenian passage.

INTRODUCTION

In any detailed analysis of a manned circumlunar mission it is desirable to establish, as soon as possible, a series of nominal precision trajectories compatible with the overall scope of such a mission. These nominal trajectories may then be used as a realistic take-off point for detailed guidance and navigation studies, error analyses, abort considerations, and other associated problems.

The purpose of this report is to present the characteristics of three precision trajectories suitable for use in the study of a manned circumlunar mission in the year 1968. Each of these trajectories satisfies the constraints of launch from Cape Canaveral, Florida, and touchdown in the continental United States. Third-quarter lighting conditions were chosen for each case, and the specified declinations of the moon were varied from a value prior to the maximum negative declination to approximately the same value after the occurrence of maximum negative declination. In obtaining these trajectories, use has been made of a four-body, three-dimensional trajectory program utilizing actual calendar dates and celestial body positions as obtained from U.S. Naval Observatory data.

TRAJECTORY ANALYSIS

Computing Procedure

The trajectory calculations for the present paper are based on a numerical integration of the equations of motion of a vehicle in three-dimensional earth-moon space and under the gravitational influence of the sun, the moon, and an oblate earth. In performing the calculations, use has been made of a computing program obtained by the modification of the interplanetary trajectory program described in reference 1. This program employs Encke's formulation of the governing differential equations, which is characterized by the integration of the perturbations of the vehicle from a reference two-body orbit. When these perturbations become larger than a specified value, a new reference two-body path is chosen. As an aid in keeping the perturbations small, the reference point for the two-body orbit is changed from the earth to the moon during that position of the trajectory when the moon exerts the strongest gravitational attraction.

The trajectory-program specifications and the values of the terrestrial and lunar physical constants which were used to obtain the results presented in this paper are given in table I. Positions of the sun, moon, and earth were obtained from U.S. Naval Observatory data.

The initial estimate of the injection conditions used in the determination of each of the trajectories was obtained from a two-body analysis, a massless moon being assumed. The initial estimate of the time of injection was determined by an iterative technique by using an approximate value obtained from reference 2 for the desired declination and surface lighting condition at periselenian passage. These initial conditions were then varied until a trajectory was obtained which satisfied the desired reentry conditions.

Design Specifications

In designing the trajectories the following specifications were initially established:

(1) Launch would take place at Cape Canaveral in the year 1968 with trajectory characteristics compatible with the capabilities of a booster such as the Saturn vehicle

(2) Injection would take place from a direct launch, that is, no coasting orbits would be considered

(3) Periselenian passage would occur at or near the third quarter lighting of the moon

(4) Reentry conditions would be suitable for manned missions

(5) Vehicle touchdown would occur in the continental United States.

The range safety considerations associated with a launch from Cape Canaveral and the specification of a direct launch restrict the time of injection to those periods when the moon is at or near maximum negative declination. (See ref. 3.) In addition, the requirement of a specified lunar lighting condition establishes the time or date during a specific year when injection may take place. (See ref. 2.)

The specification of a desired touchdown location and the declination of the moon at the time of periselenian passage have a significant effect on the design of the trajectory. As noted in reference 4 the specification of these quantities, for a designated reentry trajectory range, dictates the value of the inclination of the trajectory plane to the earth's equatorial plane on the earth-return portion of the mission. For the trajectories considered in this paper, the required inclinations to achieve a touchdown point in the continental United States lie between 40° and 50° for reentry trajectory ranges (angular travel from reentry to vehicle touchdown) between 40° and 60°.

RESULTS AND DISCUSSION

Trajectory Characteristics

The characteristics of each trajectory are given in table II. For identification purposes, the trajectories have been numbered from 1 to 3, and the order of presentation is by injection date. The selection of the injection dates was based on the desirability of presenting the trajectory characteristics for lunar positions associated with each of the three types of lunar motion which may be encountered with a direct launch from Cape Canaveral, that is, whether the moon is descending, ascending or at maximum negative declination. Thus, for trajectory 1, the moon has a declination of -19° and is descending; for trajectory 2, the moon is at the position of maximum negative declination of -28.4°; and for trajectory 3, the moon has a declination of -18.4° and is ascending.

The earth trace of each trajectory during the initial and final phases of the mission is shown in figure 1. The traces of these trajectories are very similar to each other. Vehicle launch takes place at Cape Canaveral and injection occurs somewhere over the Atlantic Ocean. The turnaround point of the earth trace occurs near South Africa. It is to be noted that the vehicle can be tracked from the Johannesburg station for a period of several hours during the initial portion of the flight. The turnaround point of the earth trace during the final phase of the mission is near Australia and excellent tracking coverage will be possible from the Woomera station for several hours prior to reentry. Reentry, at an altitude of 400,000 feet, takes place over the Pacific Ocean at a point somewhat south of Hawaii and vehicle touchdown occurs in the continental United States. No detailed consideration has been given here to the actual reentry trajectory (reentry to touchdown) which will be followed. This portion of the mission is represented by a dashed line in figure 1, and ranges of 20°, 40°, and 60° from reentry are indicated. Flight time from injection to reentry, in each case, is a little over 6 days.

The spatial trace of each trajectory in an inertial coordinate system is shown in figure 2. The origin of the coordinate system is at the center of the earth. The X-axis is in the direction of the mean equinox of January 0, 1967, The XY plane is in the equatorial plane of the earth, and the Z-axis is in the direction of the earth's North Pole. This figure shows the overall characteristics of the trajectories in space, and the relative position of the vehicle and the moon at specified flight times.

The spatial trace of each trajectory is also shown in a rotating coordinate system in figure 3. The origin of the coordinate system in this figure is at the center of the earth, the X_r-axis lies along the earth-moon line, the X_rY_r plane is in the earth-moon plane, and the Z_r-axis is directed in a northerly direction so as to form a right-hand system. The traces of the trajectories in the vicinity of the moon in this coordinate system are shown in figure 4 to greater detail. The corresponding earth trace of each trajectory during the time intervals specified in this figure is shown in figure 1.

Several points of general interest may be noted from an examination of figures 3 and 4 and the trajectory characteristics given in table II. The required vehicle injection velocity increases as the position of the moon, at the time of periselenian passage, changes from a location ahead of the point of maximum negative declination (moon descending) to a location behind this point (moon ascending). For the range of lunar declinations considered in this paper, this velocity increase amounted to 59 feet per second.

The magnitude of the required injection velocity, for a given lunar target position, is primarily the result of two trajectory design considerations. First, the total mission flight time must be such that reentry occurs at the desired earth longitude, and second, the magnitude of the inclination of the return trajectory plane to the earth's equatorial plane must lie within a specified range. The change in injection velocity which is required as the moon's motion changes from a descending to an ascending mode is attributed to the fact that the energy of the trajectory must be increased to offset the moon's vertical motion and still maintain the desired inclination between the vehicle trajectory plane and the earth's equatorial plane.

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The decrease in periselenian distance corresponding to the noted change in injection velocity amounted to 563 miles. Since the total mission flight time was approximately the same in each case, it is apparent that some control of the periselenian distance may be obtained by a variation in the choice of the lunar declination at the time of periselenian passage.

From an examination of figures 3 and 4, it may be noted that the inclination of the vehicle trajectory plane to the earth-moon plane on the outbound portion of the mission is much higher for trajectory 1 than for trajectories 2 and 3. This condition is the result of the designation of a direct launch from Cape Canaveral. The magnitude of this inclination decreases rapidly as the moon approaches its position of maximum negative declination. (See ref. 3.) It may also be noted that with trajectory 1 the vehicle approaches the moon from beneath the earth-moon plane whereas with trajectories 2 and 3 the vehicle approaches the moon from above the earth-moon plane.

Precision of Results

Two factors which could affect the precision of the results presented in this paper are the magnitude of the values selected for the trajectory program specifications (in particular, the integration interval and the allowable limit of the perturbation ratios), and the perturbing effect of other planets. To determine the effect of a change in the program specifications from the values recommended in reference 1, trajectory 3 was recomputed with a value for the allowable limit of the perturbation ratios of one-half that listed in table I and with an integration interval, for vehicle positions in earth reference but at a distance greater than 20 earth radii, of one-fourth the value given in table I. This procedure resulted in a change of only -0.13 mile in the magnitude of the return perigee distance and a negligible change in the total flight time; therefore the values given in table I are satisfactory.

In order to determine the effect of restricting the trajectory program to a four-body calculation, trajectory 2 was rerun to include the perturbing effects of the planets Venus, Mars, and Jupiter. This procedure resulted in a change in earth perigee on the return flight of 0.86 mile and a negligible change in total flight time.

CONCLUDING REMARKS

The trajectories which are presented in this paper are intended to serve as a guide in the analysis of a manned circumlunar mission. The characteristics of these trajectories are subject to the constraints of a direct launch from Cape Canaveral, Florida, and vehicle touchdown in the continental United States. Within the limits of these constraints, the trajectory characteristics are representative of the actual conditions associated with a circumlunar mission. The periselenian values which were obtained are typical of those which would be required for the initial series of manned circumlunar flights.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Air Force Base, Va., December 8, 1961.

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2. Woolston, Donald S.: Declination, Radial Distance, and Phases of the Moon for the Years 1961 to 1971 for Use in Trajectory Considerations. NASA TN D-911, 1961.

3. Tolson, Robert H.: Effects of Some Typical Geometrical Constraints on Lunar Trajectories. NASA TN D-938, 1961.

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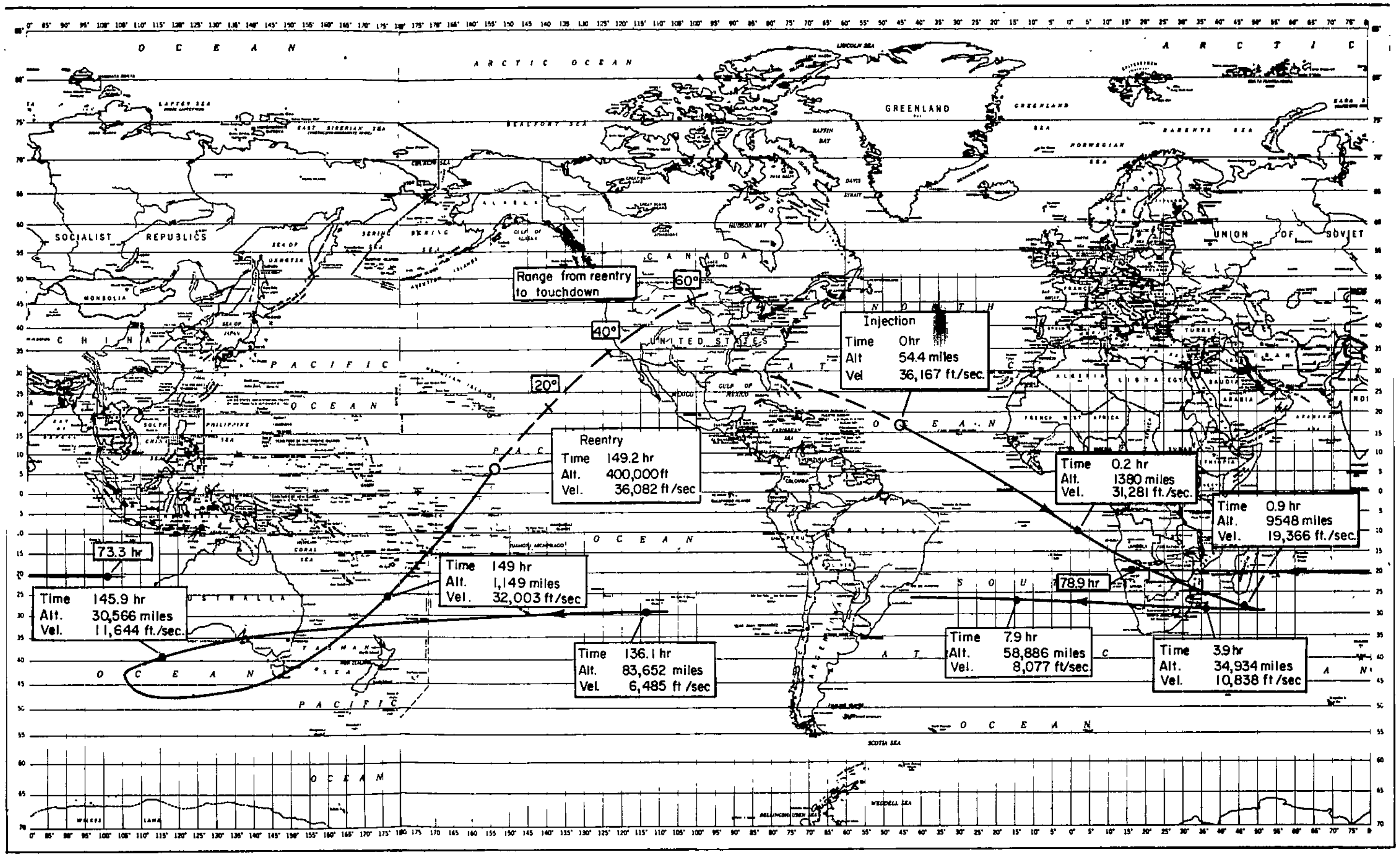
TABLE I.- TRAJECTORY PROGRAM SPECIFICATIONS AND PHYSICAL CONSTANTS

Gravitational radius of earth, statute miles	3,963.21
Geocentric gravitational constant, ft^3/sec^2	1.407654×10^{16}
Ratio of mass of earth to mass of moon	81.45
Radius of moon, statute miles	1,079.99
Base time	Midnight, January 0, 1967
Integration interval near earth (within 20 earth radii) or in moon reference, hr	0.015625
Integration interval in earth reference other than above, hr	1.0
Allowable limit for the ratios of position, velocity, and acceleration perturbations to the corresponding two-body values	0.01

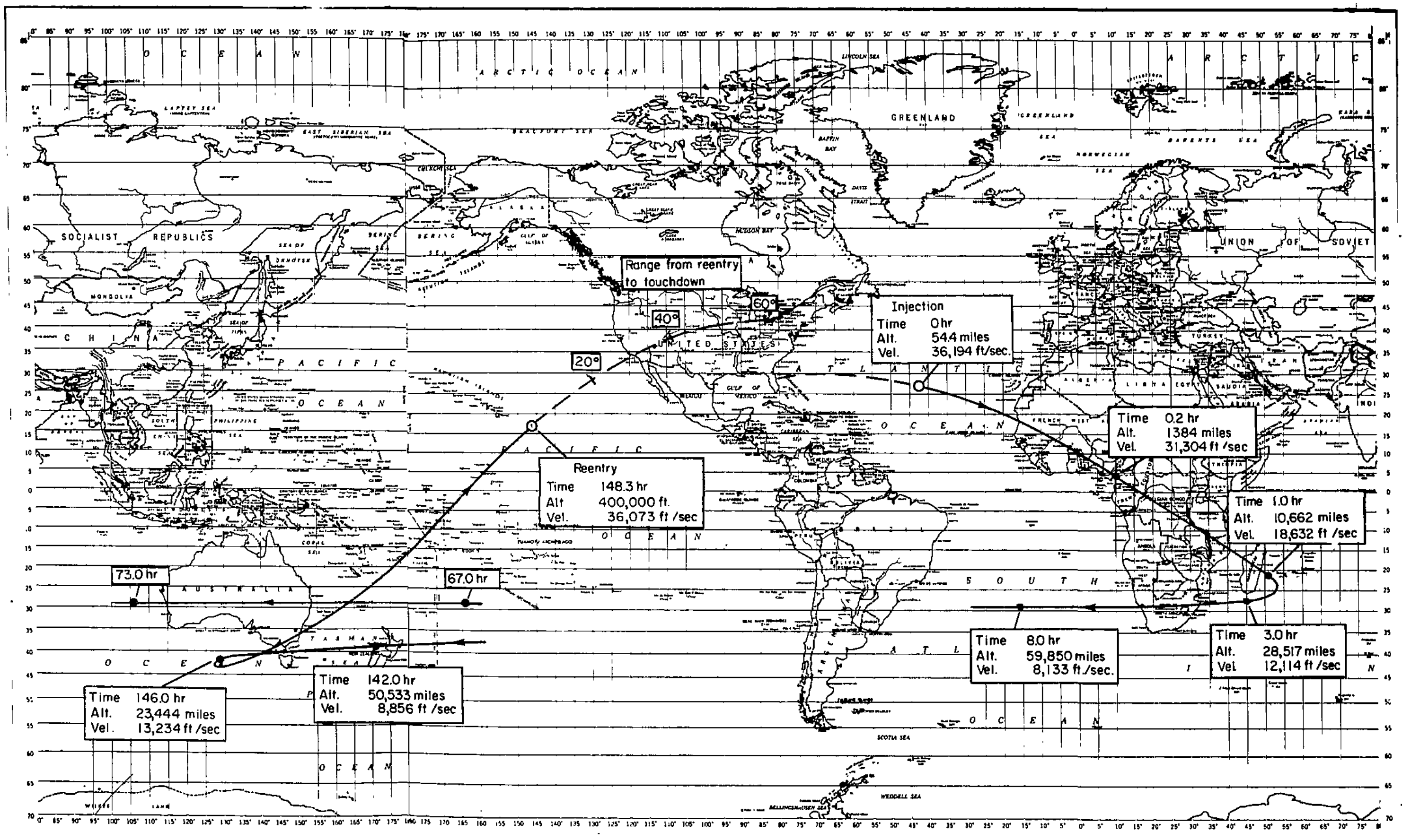
TABLE II.- CHARACTERISTICS OF TRAJECTORIES

	Trajectory 1	Trajectory 2	Trajectory 3
Launch conditions:			
Latitude, Cape Canaveral	28.278° N	28.278° N	28.278° N
Longitude, Cape Canaveral	80.574° W	80.574° W	80.574° W
Heading angle	98.88°	82.82°	109.74°
Time to injection	785.0 sec	785.0 sec	785.0 sec
Angular travel to injection	37.0°	37.0°	37.0°
Injection conditions:			
Time	January 20, 1968 $22^h55^m27.0^s$ u.t.	March 18, 1968 $22^h27^m15.0^s$ u.t.	May 15, 1968 $22^h10^m33.3^s$ u.t.
Latitude	17.25° N	26.40° N	11.50° N
Longitude	45.35° W	42.04° W	48.51° W
Heading angle	114.34°	102.71°	122.20°
Altitude	54.43 miles	54.43 miles	54.43 miles
Velocity (inertial)	36,167 ft/sec	36,194 ft/sec	36,226 ft/sec
Elevation angle	1.7°	1.7°	1.7°
Periselenian conditions:			
Time from injection	76.2 hr	70.6 hr	68.2 hr
Distance from center of moon	2,387.95 miles	2,113.21 miles	1,824.46 miles
Declination of the moon	-19.0°	-28.4°	-18.4°
Velocity with respect to moon . . .	6,228 ft/sec	6,496 ft/sec	6,921 ft/sec
Reentry conditions:			
Time from injection	149.15 hr	148.34 hr	149.63 hr
Altitude	400,000 ft	400,000 ft	400,000 ft
Angle	-5.83°	-7.56°	-6.1°
Latitude	6.4° N	15.8° N	9.1° N
Longitude	154.6° W	147.2° W	164.7° W
Velocity (inertial)	36,082 ft/sec	36,073 ft/sec	36,076 ft/sec



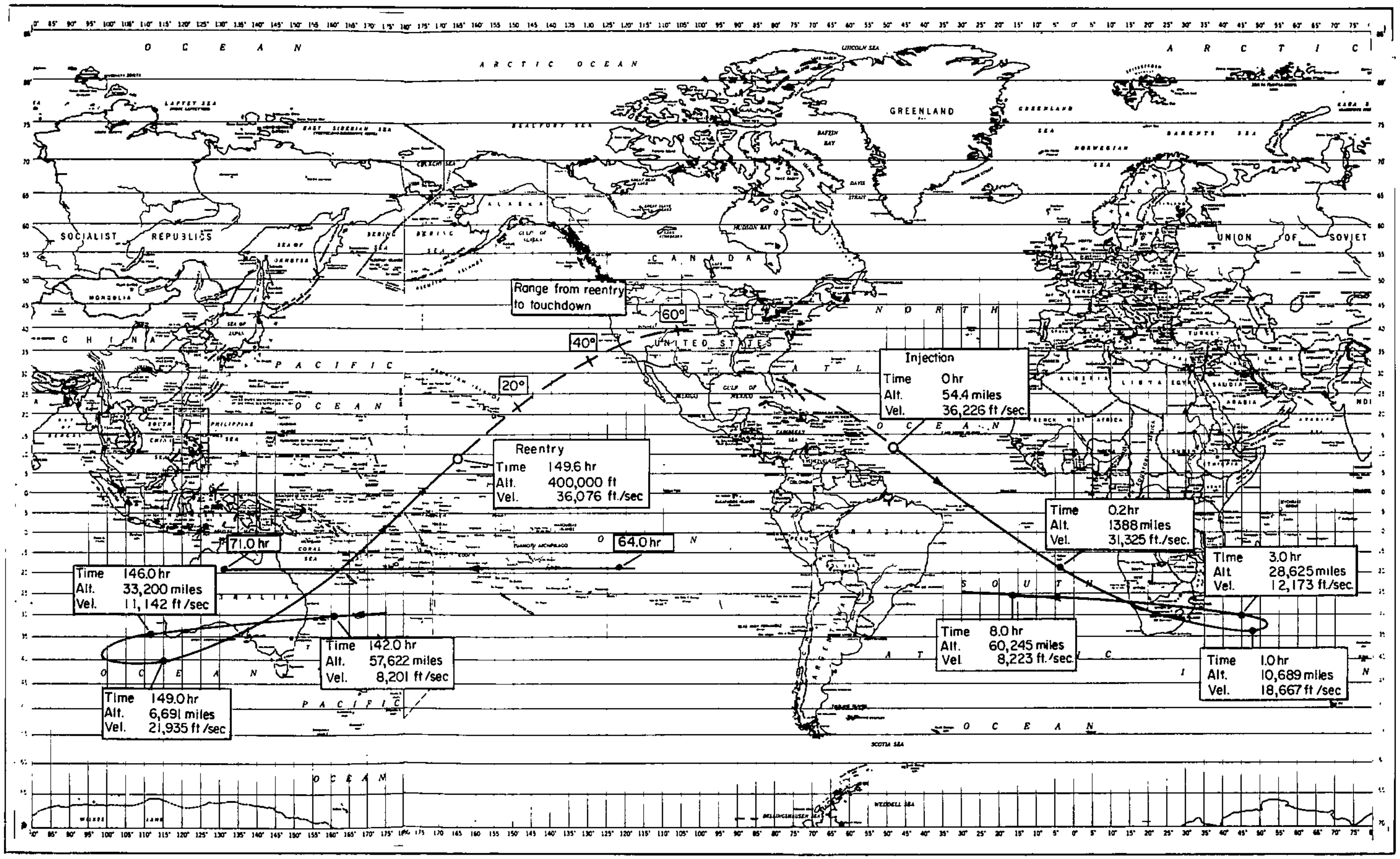
(a) Trajectory 1.

Figure 1.- Earth trace during the initial and final phases of the mission.



(b) Trajectory 2.

Figure 1.- Continued.



(c) Trajectory 3.

Figure 1.- Concluded.

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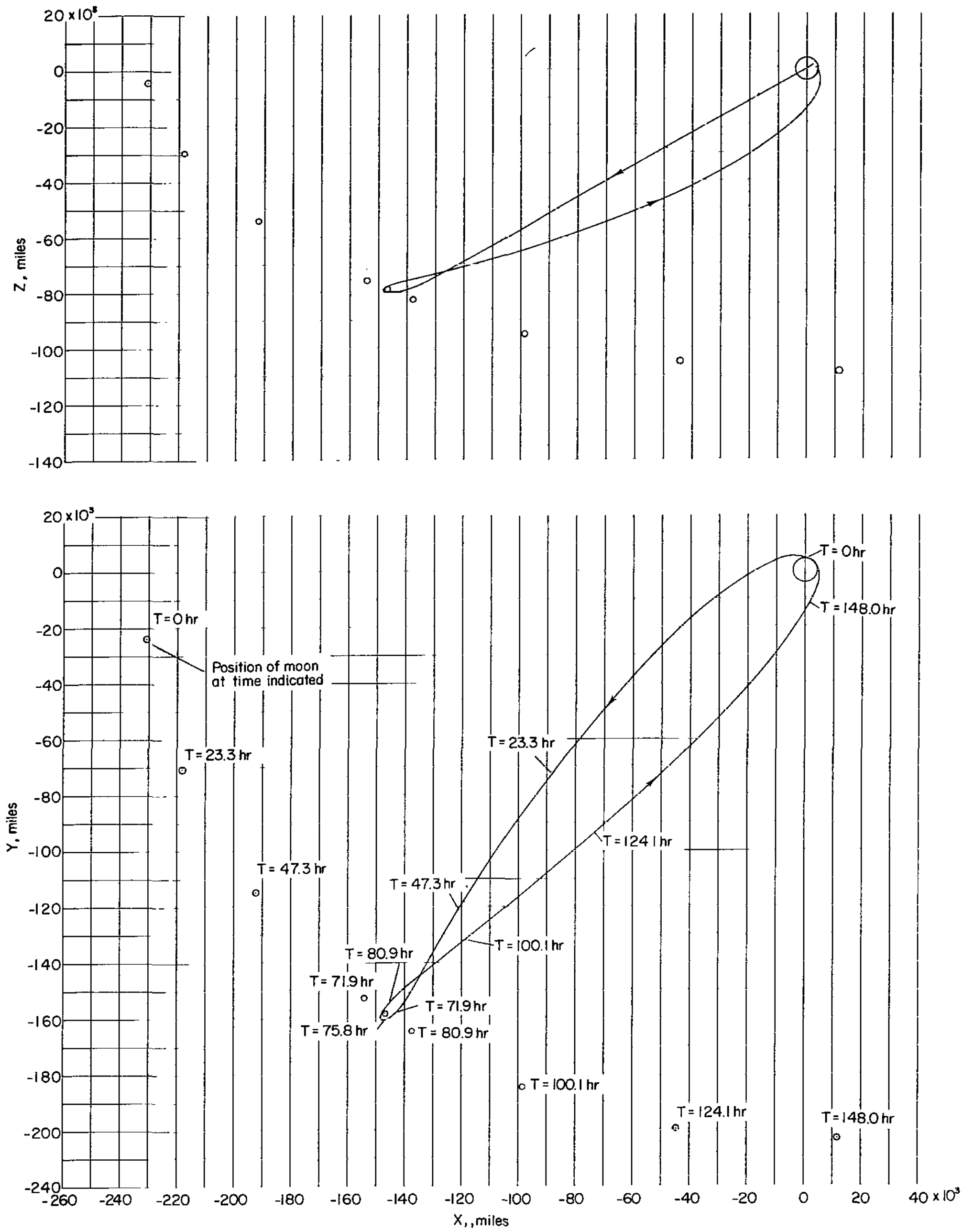

(a) Trajectory 1.

Figure 2.- Spatial trace on an inertial coordinate system. T denotes time from injection. (XY plane is in the earth's equatorial plane.)

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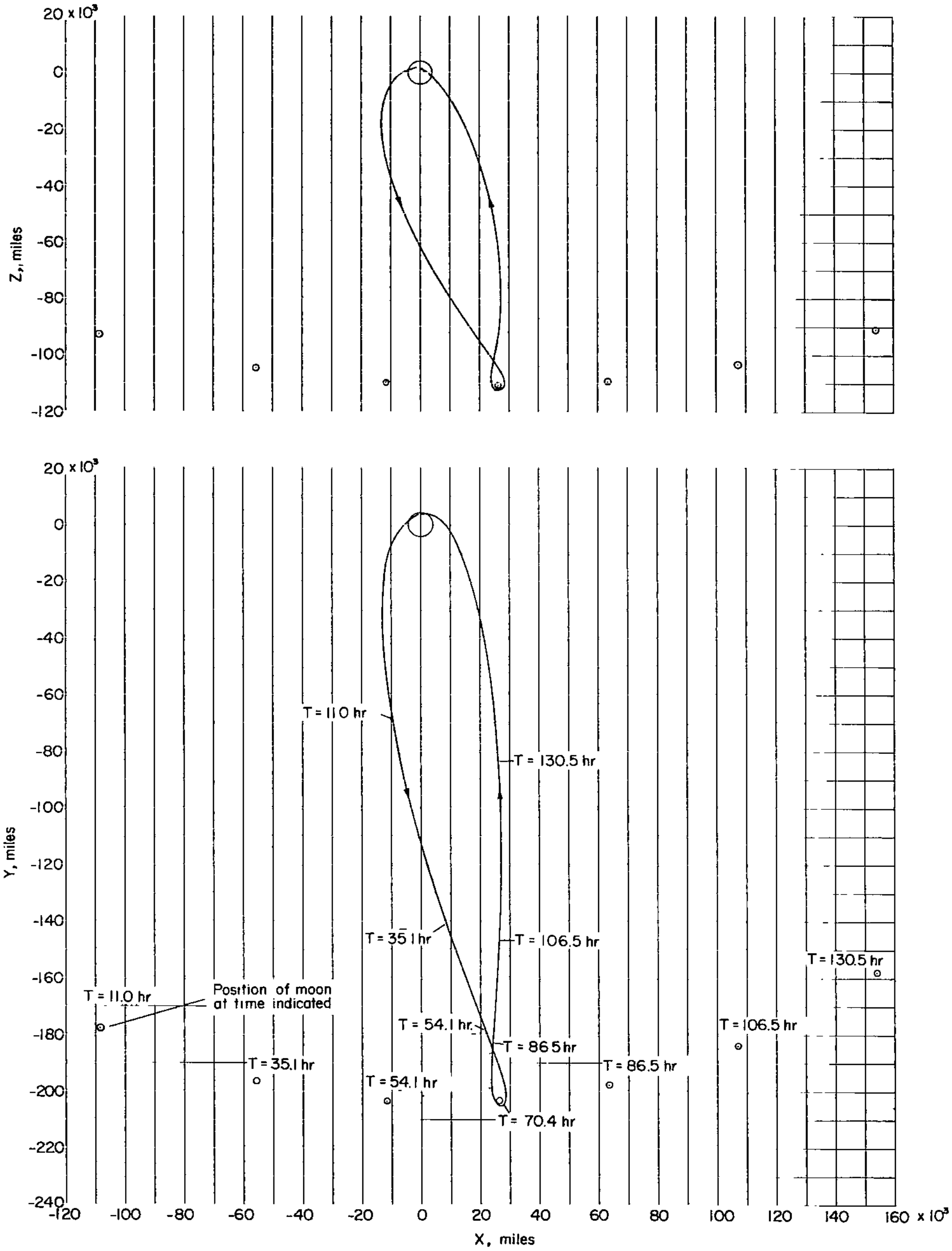
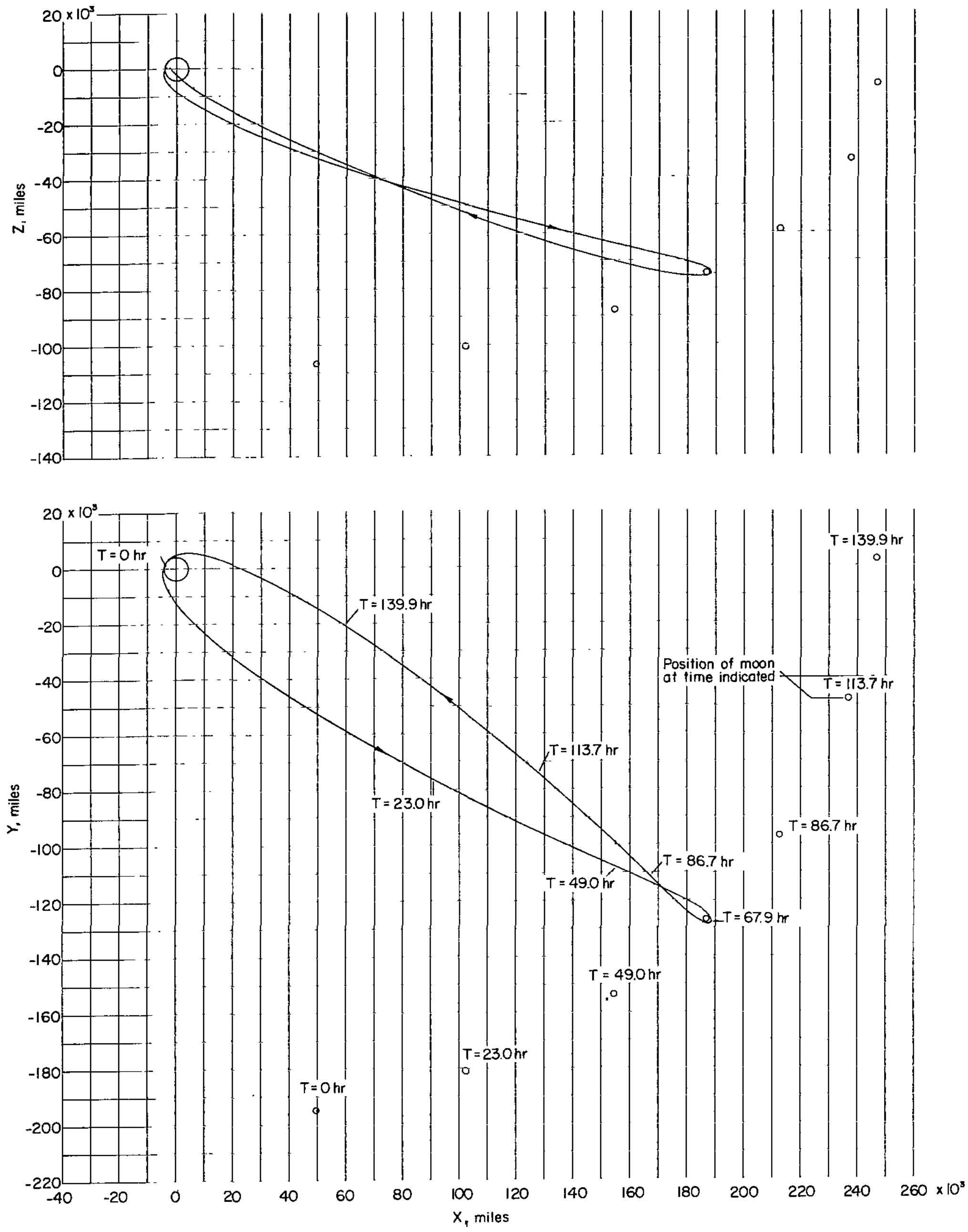


(b) Trajectory 2.

Figure 2.- Continued.



(c) Trajectory 3.

Figure 2. Concluded.

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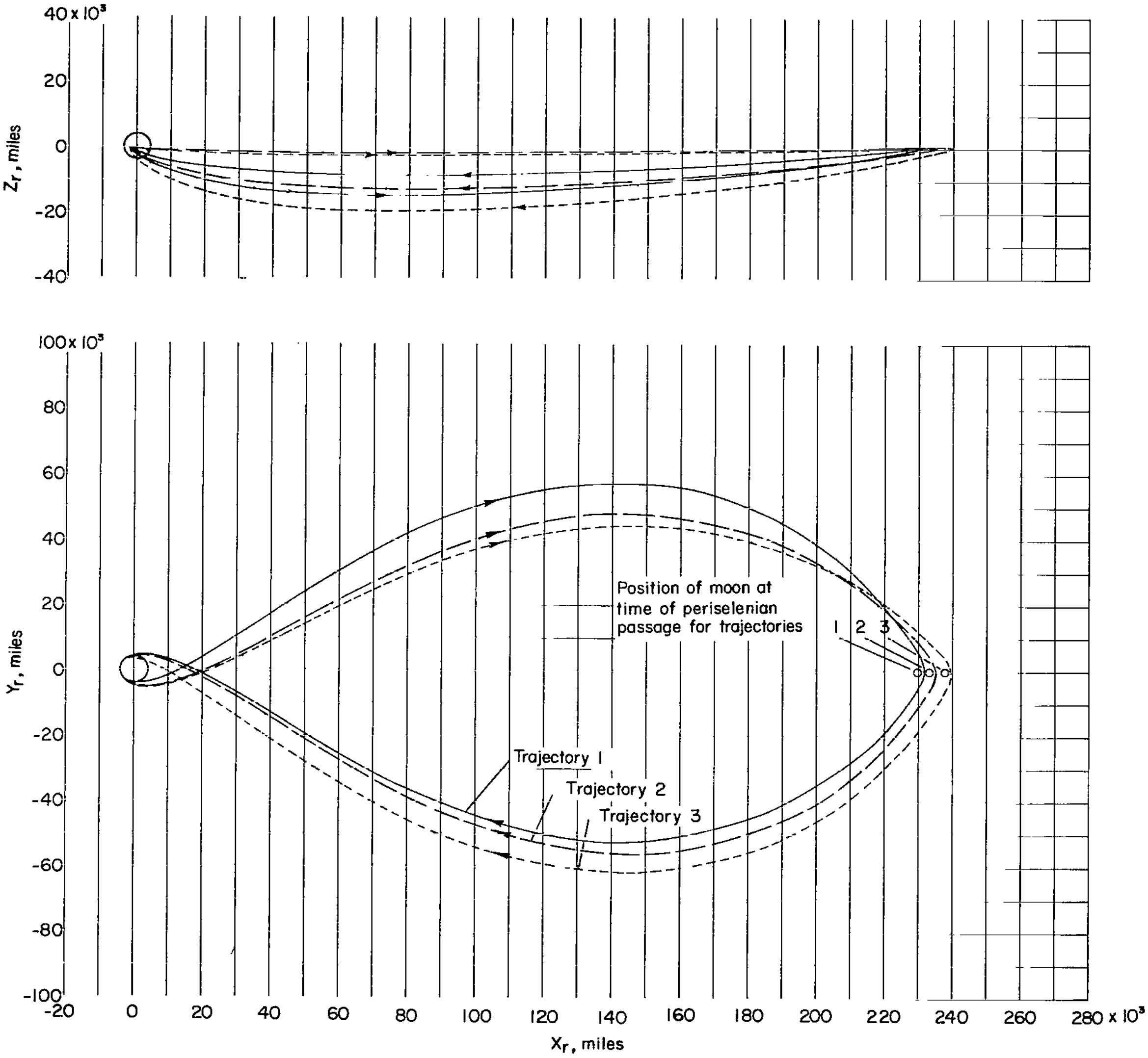

Figure 3.- Spatial trace of trajectories in a rotating coordinate system.

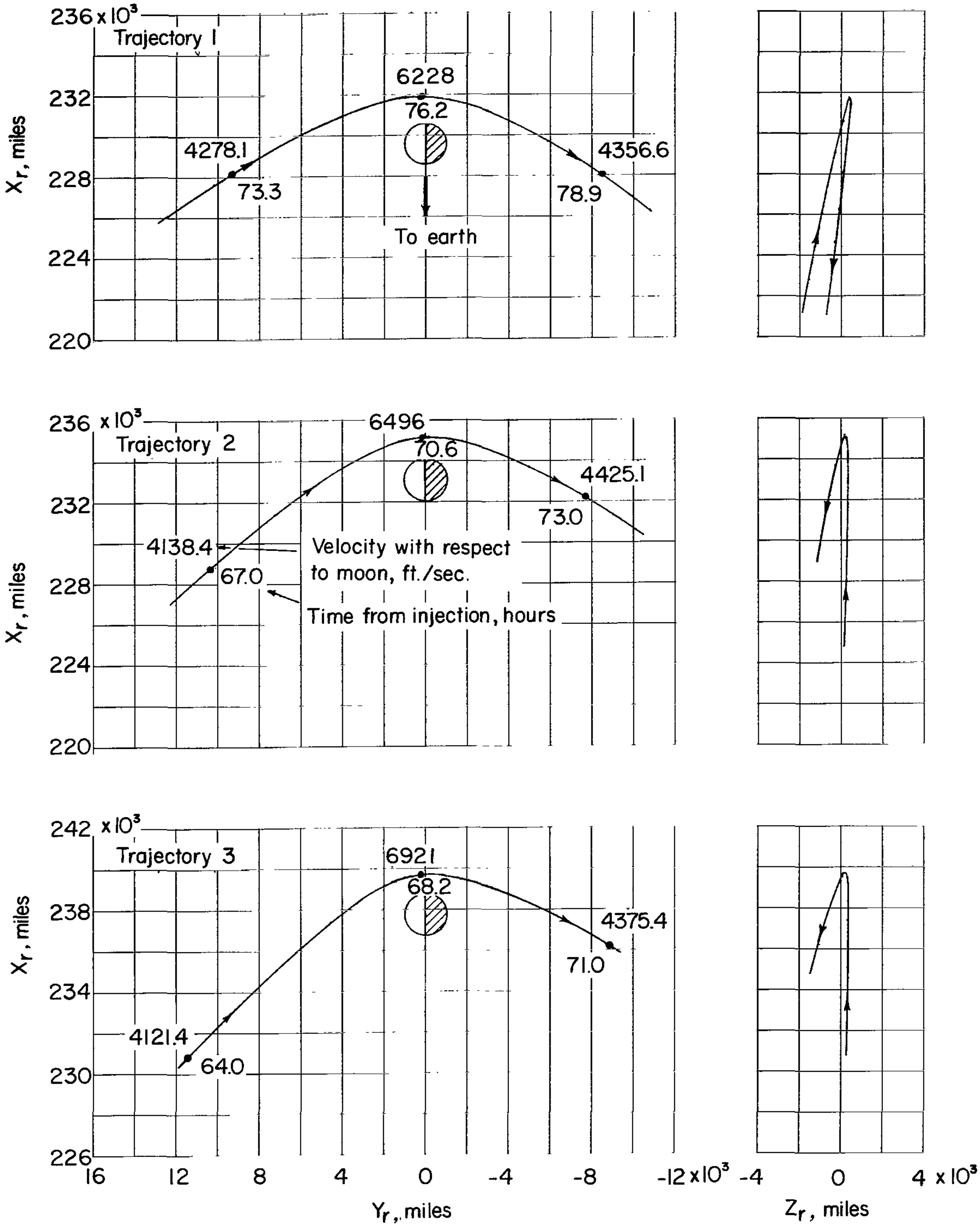

Figure 4.- Trajectory characteristics near the moon.